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Kaewunruen, Sakdirat; Akono, Ange-Therese; Remennikov, Alex

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Attenuation effect of material damping on impact vibration responses of railway concrete sleepers

Sakdirat Kaewunruen[1], PhD; Ange-Theres Akono[2], PhD and
Alex M Remennikov[3], PhD

[1]Senior Lecturer in Railway and Civil Engineering, School of Engineering, the University of Birmingham, Birmingham, United Kingdom, s.kaewunruen@bham.ac.uk
[2]Associate Professor of Civil Engineering, Northwestern University, Chicago, Illinois, USA.
[3]Head of School, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW, Australia.

ABSTRACT: In railway industry, high strength concrete has been adopted for track slabs and railway sleepers for more than half a century. Prestressed concrete sleepers (or railroad ties) are designed usually using high strength concrete (> 55 MPa) in order to carry and transfer the wheel loads from the rails to the ground and to maintain rail gauge for safe train travels. In general, the railway sleepers are installed as the crosstie beam support in ballasted railway tracks. Statistically, they are subjected to impact loading conditions induced by train operations over wheel or rail irregularities, such as flat wheels, dipped rails, crossing transfers, rail squats, corrugation, etc. These defects can be commonly found during the operational stage of life cycle. The magnitude of the shock load depends on various factors such as axle load, types of wheel/rail imperfections, speeds of vehicle, track stiffness, etc. This paper demonstrates the investigations into the dynamic responses of *in-situ* prestressed concrete sleepers using high strength materials, particularly under a variety of impact loads. The nonlinear finite element model of full-scale prestressed concrete sleeper with the realistic support condition has been developed using a finite element package, STRAND7. It has been verified by the experiments carried out using the high capacity drop-weight impact machine and experimental modal testing. The experimental results exhibited very good correlation with numerical simulations. In this paper, the numerical studies are extended to evaluate the dynamic behaviors of high strength concrete sleepers modified by crumb rubbers to increase material damping coefficients. The outcome of this study can potentially lead to the utilization and practical design guideline of high strength concrete engineered by crumb rubber from wasted tires and plastics for prestressed concrete sleepers.

INTRODUCTION

Without a doubt, the majority of civil infrastructure is constructed out of concrete, currently at a rate of 2 billion tonnes per year (Chung, 1995). This is somehow responsible for 5% of global carbon dioxide emissions annually (Kaewunruen et al., 2017). However, it is well known that concrete has several disadvantages such as low tensile strength, low ductility, brittle, low damping (low energy dissipation), and high susceptibility to cracking. This causes the structure to deteriorate and lose its integrity when subjected to repeated harsh environmental conditions and dynamic loading conditions (Remennikov and Kaewunruen, 2008; Kaewunruen, 2014; Meesit and Kaewunruen, 2017). Thus, when exposed to these high-intensity conditions, concrete structures are at a risk of failure. In addition, the high global usage of concrete material combined with the large amount of pollution its production produces every year is a major concern. Paris Agreement in 2016 has imposed the limit of carbon emission so that global warming can be limited to be less than 2°C in 2100 (Binti Saadin et al., 2016a; 2016b). This implies that the use of high-carbon materials such as cement should be even more efficient and effective as much as possible. Therefore a sustainable approach needs to be taken to find solution to these existing issues in material production and selection for design and manufacturing (Kaewunruen and Lee, 2017). The sustainable approach within this study involves developing a method to reduce carbon emissions and to improve the resilience of concrete structures. This study comprises of novel concrete innovation incorporating waste materials (see Fig.1) for the purposes of reducing carbon emissions and also improving damping of concrete (Kaewunruen and Kimani, 2017; Kaewunruen et al., 2018a).

FIG. 1. Waste car tyres for recycling

A vital safety-critical component of railway track structures is railway sleepers (also called ‘railroad tie’ in North America). Railway sleepers are the cross beam element supporting rails in order to provide load support and to secure rail gauge. Today, the most common material for manufacturing sleepers is concrete (Kaewunruen et al., 2014; You et al., 2017). The experience of design and application of railway concrete sleepers have been over 60 years around the world. Their key functions are to redistribute loads from the rails onto the underlying ballast bed, and to secure rail gauge for safe and smooth train passages. Based on the current design approach using static and quasi-static theory of solid mechanics, the design life span of the concrete sleepers is targeted at around 50 years in Australia and around 70 years in Europe (Standards Australia, 2003; British Standards Institute, 2016). In design practice, dynamic problems have not fully been taken into account, giving rise to the lack of new innovation for concrete sleepers. Current industry practice is still based on the topological optimisation using static analysis and the selection of tailored or bespoke dynamic factors for quasi-static design (Remennikov et al., 2012; Kaewunruen and Remennikov, 2009; Wolf et al., 2015; Vu et al., 2016). This is because the current design and testing standards are rather primitive and overly simplified. Fig. 2 shows a typical ballasted railway tracks. The track superstructure includes rail, rail pads, fasteners, sleepers and ballast; and the track substructure contains ballast mat, subballast (or capping layer), geosynthetics, subgrade and formation.

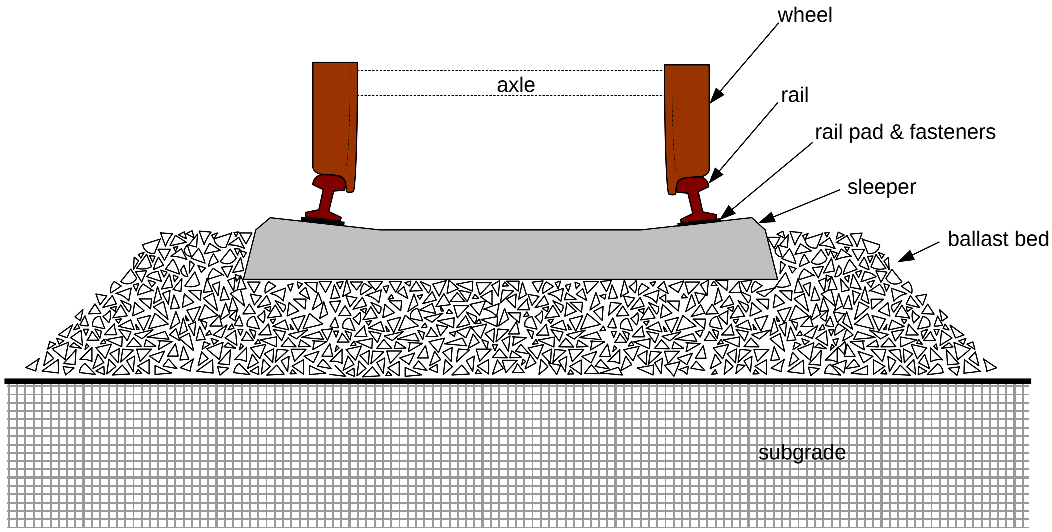


FIG. 2. Typical ballasted track

Despite the fact that the railway sleepers are exposed to dynamic loading conditions (Remennikov and Kaewunruen, 2008), the material damping aspect has never been fully investigated. This paper is the first to present an advanced railway concrete sleeper modeling capable of analysis into the vibration attenuation effects of dynamic loading on the dynamic behaviors of railway concrete sleepers. The emphasis of this study is placed on the nonlinear dynamic flexural responses of railway concrete sleepers subjected to effective viscous damping of concrete material. It is the first time that the responses of concrete sleepers incorporating material damping have been investigated. The insight into the vibration attenuation will help structural and track engineers making a better choice in advanced material design and selection. It will also inspire materials engineers to further improve the dynamic material capabilities.

NONLINEAR MODELLING

A number of extensive studies recommended that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers under vertical loads (Neilsen, 1991; Cai, 1992; Grassie, 1995; Manalo et al., 2012). In this investigation, the finite element model of *in-situ* concrete sleeper (optimal length of 2.5m) has been previously developed and calibrated against the numerical and experimental modal parameters (Kaewunruen and Remennikov, 2006a; 2006b; 2008a; 2008b). Fig. 3 illustrates the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 (G+D, 2001), the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the realistic concrete sleeper. The trapezoidal cross-section was assigned to the sleeper elements. The rails and rail pads at railseats were simulated using a series of spring. In this study, the sleeper behaviour is stressed so that very small stiffness values were assigned to these springs. In reality, the ballast support is made of loose, coarse, granular materials with high internal friction. It is often a mix of crushed stone, gravel, and crushed gravel through a specific particle size distribution. It should be noted that the realistic ballast provides resistance to compression only (Kaewunruen and Remennikov, 2008b).

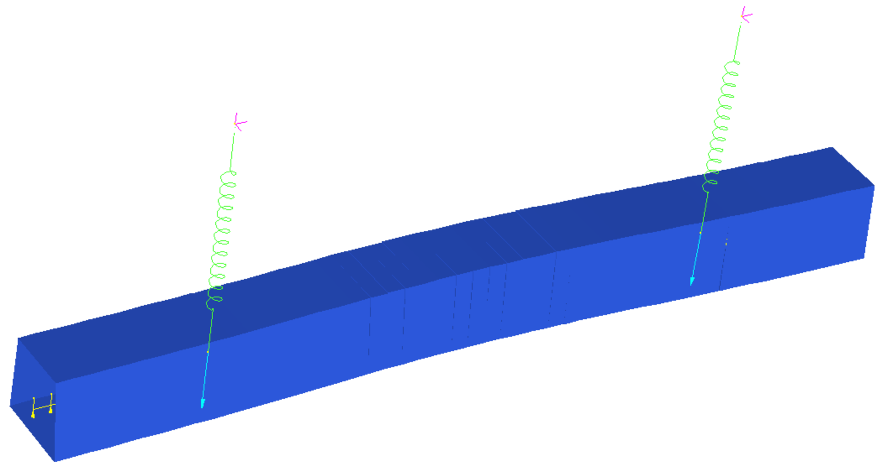


FIG. 3. STRAND7 finite element model of a prestressed concrete sleeper

In this study, the realistic support condition is simulated using the tensionless beam support feature in STRAND7. This attribute allows the beam to lift or hover over the support while the tensile supporting stiffness is omitted. This attribute creates nonlinear boundary conditions to the sleeper model, requiring Newton Raphson's numerical iterations to resolve the sleeper-ballast contact perimeter. The tensionless support option can correctly represent the ballast characteristics in real tracks. Table 1 shows the geometrical and material properties of the finite element model. It is important to note that the parameters in Table 1 give a representation of a specific rail track. These data have been validated and the verification results have been presented elsewhere (Kaewunruen and Remennikov, 2006a; 2008a).

Table 1 Engineering properties of the standard sleeper used in the modeling

Parameter lists		
Flexural rigidity	$EI_c = 4.60,\ EI_r = 6.41$	MN/m^2
Shear rigidity	$\kappa GA_c = 502,\ \kappa GA_r = 628$	MN
Ballast stiffness	$k_b = 13$	MN/m^2
Rail pad stiffness	$k_p = 17$	MN/m
Sleeper density	$\rho_s = 2{,}750$	kg/m^3
Sleeper length	$L = 2.500$	m
Rail gauge	$g = 1.435$	m
Wheel load distance	$d = 1.500$	m

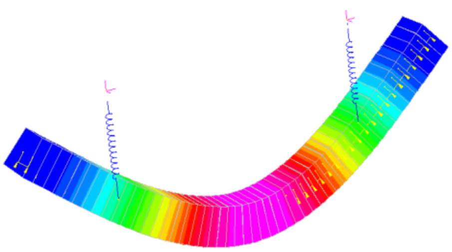
In structural design, it is common to assume that concrete material has negligible viscous damping ratio (Hesameddin et al., 2015). However, it is often found that the effective damping of high-strength concrete can be varied from 0.1% to 2% (Meesit and Kaewunruen, 2017). In general, the equation of forced motion for multi-degree-of-freedom (MDOF) system can be generalised. Taking a mass-normalized formulation approach, the acceleration measured on the structure becomes the mass-normalized inertial force. The mass-normalized velocity proportional equivalent viscous damping ratio can be written in terms of the damping coefficient and the natural period of a sub-critically structure as (Kaewunruen et al., 2018a):

$$\beta = \frac{c}{m}\frac{T_n}{4\pi} \tag{2}$$

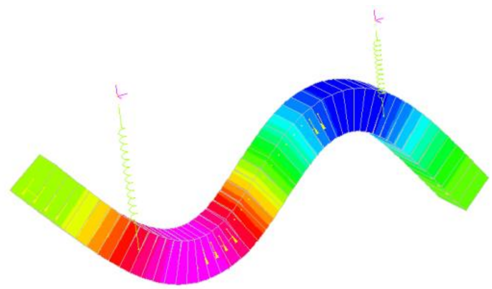
where β is the equivalent viscous damping ratio; m is the mass of structure; c is equivalent viscous damping; and T_n is the natural period of the structure (i.e. period of the dominate mode of response). In this study, the first bending mode of sleeper vibration has been used to calculate the damping ratio. The equivalent viscous damping (c) has been used in the FE modelling for transient dynamic integration in order to avoid matrix errors for explicit finite solution calculations.

RESULTS AND DISCUSSION

Free vibration analysis has been conducted to evaluate the natural frequencies and corresponding mode shapes of *in-situ* concrete sleeper. Fig. 4 shows the dominant bending modes of vibration of the sleepers. As a result, Tn is 7 msec and the mass of sleeper (m) is 354 kg.



a) 1st bending (143 Hz)



b) 2nd bending (370 Hz)

FIG. 4. Free vibration characteristics of prestressed concrete sleeper

The dual wheelset impact loads of 100 kN magnitude and 3 msec duration are applied at both railseats to stimulate impact vibrations. This impulse is equivalent to the effect of common wheel burns (e.g. 3-5mm flats) on railway tracks. The effects of material damping on the impact responses of railway concrete sleeper at railseats and at mid-span can be illustrated in Fig. 5. It is clear that material damping affects the impact responses across the frequency span. The higher the frequency the higher the loss of impact spectra. The damping of concrete can suppress well the impact vibrations at both railseats and mid-span of the concrete sleeper. This can be implied that the improvement in material damping can considerably suppress vibrations that can cause breakage of sleeper and underlying ballast. This insight can also be observed for railway bridge viaducts (Ülker-Kaustell and Karoumi, 2012; Zhai et al., 2013; Malveiro et al., 2018; Kaewunruen et al., 2018b). The dynamic load effects can be suppressed, resulting in lesser dynamic defections and bending stresses. Since the concrete sleepers are generally designed to be '*uncracked*' under serviceability limit state (i.e. dynamic impact factor of 2.0 to 2.5), the results clearly show that damping enhancement (>4% of damping ratio) can significantly improve the long-term performance and durability of the concrete sleepers.

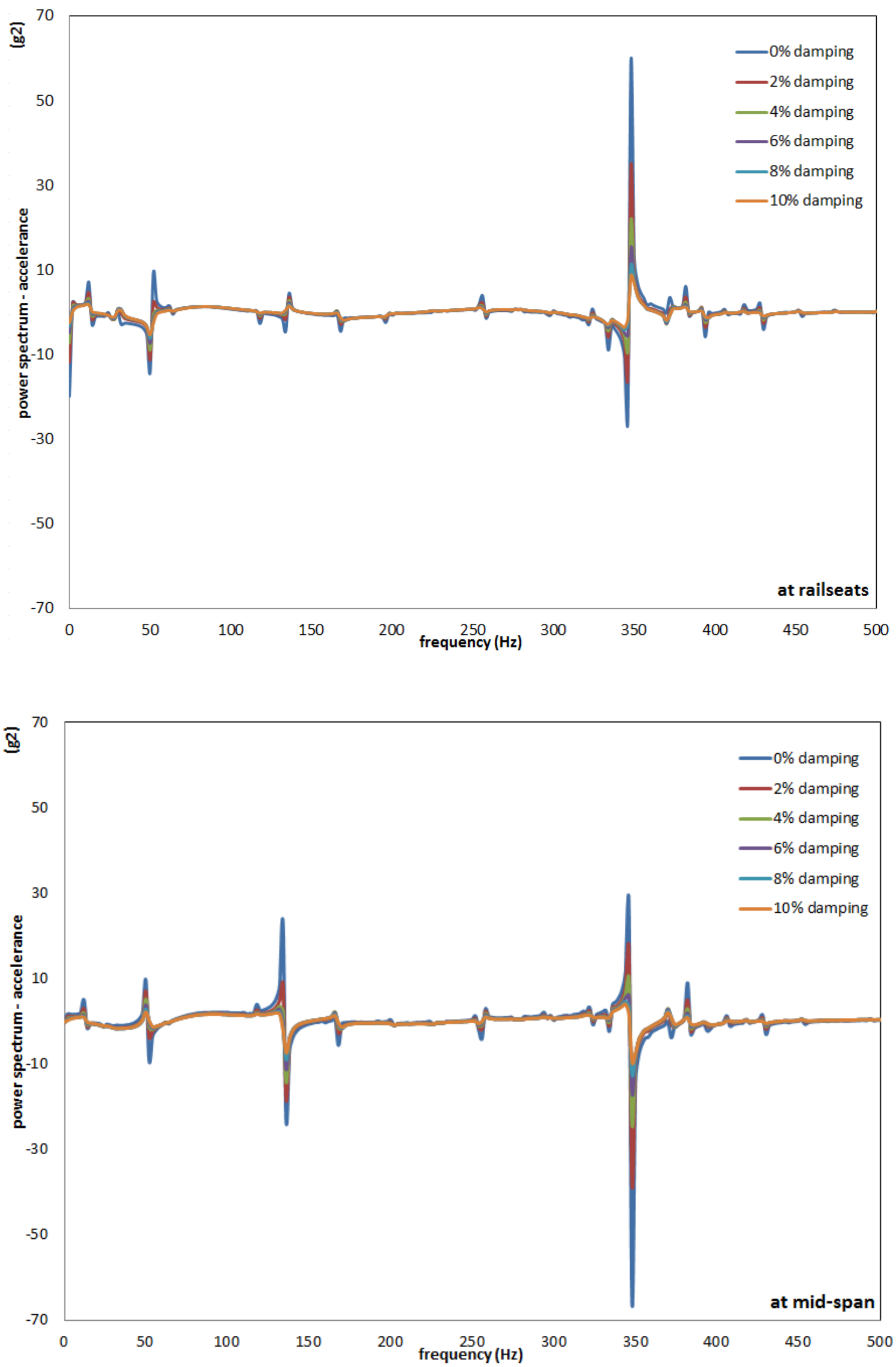


FIG. 5. Impact responses of railway concrete sleeper (frequency domain)

CONCLUSIONS

The most cost-effective railway track systems for metro, light rail, urban and suburban and freight networks are the ballasted tracks. For ballasted tracks, concrete is the most common used material for railway concrete sleepers. For over five decades, concrete sleepers are used to redistribute wheel forces onto track structure and secure track gauge for safe passages of rolling stocks. Statistically, most of the time, railway tracks experience dynamic load conditions. For design purpose, concrete material's damping characteristic is often neglected. Thus, the understanding into vibration attenuation of the sleeper due to the material damping is rather limited. The ignorance of damping has resulted in very little research into advanced concrete technology for railway applications. This study is the world first to incorporate advanced knowledge of novel concrete with high damping for dynamic design of railway concrete sleepers. This paper highlights the effects of concrete damping on the vibration attenuation of railway concrete sleepers in a track system. Using an established and validated finite element model of concrete sleepers, realistic sleeper-ballast contact conditions have been adopted for nonlinear transient analysis. This study is the first to reveal that the concrete damping can provide high level of vibration attenuation in concrete sleepers in a track system across wide range of frequencies. This insight will help structural and track engineers to make a better choice of advanced concrete and composite materials for manufacturing railway concrete sleepers.

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